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ABIOTIC & BIOTIC RESPONSES OF THE COLORADO RIVER TO CONTROLLED FLOODS AT GLEN CANYON DAM, ARIZONA, USA

T.S. MELIS,[a]* J. KORMAN[b,c] and T.A. KENNEDY[a]

[a] *US Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, Arizona 86001, USA*
[b] *Department of Zoology, University of British Columbia, Vancouver, BC, Canada V6S1J3*
[c] *Ecometric Research Inc., Vancouver, BC, Canada, V6S1J3*

ABSTRACT

Closure of Glen Canyon Dam reduced sand supply to the Colorado River in Grand Canyon National Park by about 94% while its operation has also eroded the park's sandbar habitats. Three controlled floods released from the dam since 1995 suggest that sandbars might be rebuilt and maintained, but only if repeated floods are timed to follow tributary sand deliveries below the dam. Monitoring data show that sandbars are dynamic and that their erosion after bar building is positively related with mean daily discharge and negatively related with tributary sand production after controlled floods. The March 2008 flood affected non-native rainbow trout abundance in the Lees Ferry tailwater, which supports a blue ribbon fishery. Downstream trout dispersal from the tailwater results in negative competitive interactions and predation on endangered humpback chub. Early survival rates of age-0 trout increased more than fourfold following the 2008 flood, and twofold in 2009, relative to prior years (2006–2007). Hatch-date analysis indicated that early survival rates were much higher for cohorts that emerged about 2 months after the 2008 flood relative to cohorts that emerged earlier that year. The 2009 survival data suggest that tailwater habitat improvements persisted for at least a year, but apparently decreased in 2010. Increased early survival rates for trout coincided with the increased availability of higher quality drifting food items after the 2008 flood owing to an increase in midges and black flies, preferred food items of rainbow trout. Repeated floods from the dam might sustainably rebuild and maintain sandbars if released when new tributary sand is available below the tailwater. Spring flooding might also sustain increased trout abundance and benefit the tailwater fishery, but also be a potential risk to humpback chub in Grand Canyon.

KEY WORDS: Colorado River; controlled floods; sandbars; rainbow trout; humpback chub

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INTRODUCTION AND BACKGROUND

Glen Canyon Dam (lat. 36.937, long. −111.484; Figure 1) was completed in 1963 as part of the Colorado River Storage Project Act. It was the last of the high dams built in the southwestern United States, and storage of Colorado River water in Lake Powell created one of the largest reservoirs in the United States. Between 1965 and 1990, the dam's hydropower plant was operated primarily to meet downstream water supply requirements of the 1922 Colorado River Compact and to provide power in the southwestern United States. Operation of the dam has altered the Colorado River in a number of ways, including (1) changing the river's seasonal flow pattern by decreasing high spring flows (Figure 2), but increasing flow in summer and winter (Topping *et al*., 2000b); (2) eliminating lesser Grand Canyon floods that occurred in late summer and fall caused by flooding tributaries, such as the San Juan River (Topping *et al*., 2003); (3) greatly decreasing the sand supplied and transported to Marble and Grand Canyons, while also increasing sand-transport capacity by nearly doubling the river's median discharge through the 1990s (Topping *et al*., 2000a, 2000b, 2003); and (4) changing water temperatures (decreased summer and increased winter water temperatures) such that pre-dam seasonal water temperature variability has been nearly eliminated (Vernieu *et al*., 2005).

Alteration of the physical environment below Glen Canyon Dam began following dam closure in 1963. However, one of the more dramatic changes occurred when a series of channel-cleaning flows were released in spring 1965 (Figure 3a). A decade before concerns emerged about sandbar erosion in Grand Canyon National Park, the 1965 channel-cleaning flows scoured sand- and gravel-sized sediment from the bed of the first 25 km of river channel downstream of the dam (Pemberton, 1976; Grams *et al*., 2007, 2010c). This reach, which extends from Glen Canyon Dam downstream to the confluence with the Paria River (river mile (RM) 1; Figure 1), is called the Lees Ferry tailwater. As documented by Topping *et al*. (2000a), the spring 1965 high flows released from the dam were highly effective in cleaning fine sediment from the channel bed of the tailwater before non-native rainbow trout were

*Correspondence to: T.S. Melis, US Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, 2255 North Gemini Dr., Flagstaff, AZ 86001, USA
E-mail: tmelis@usgs.gov

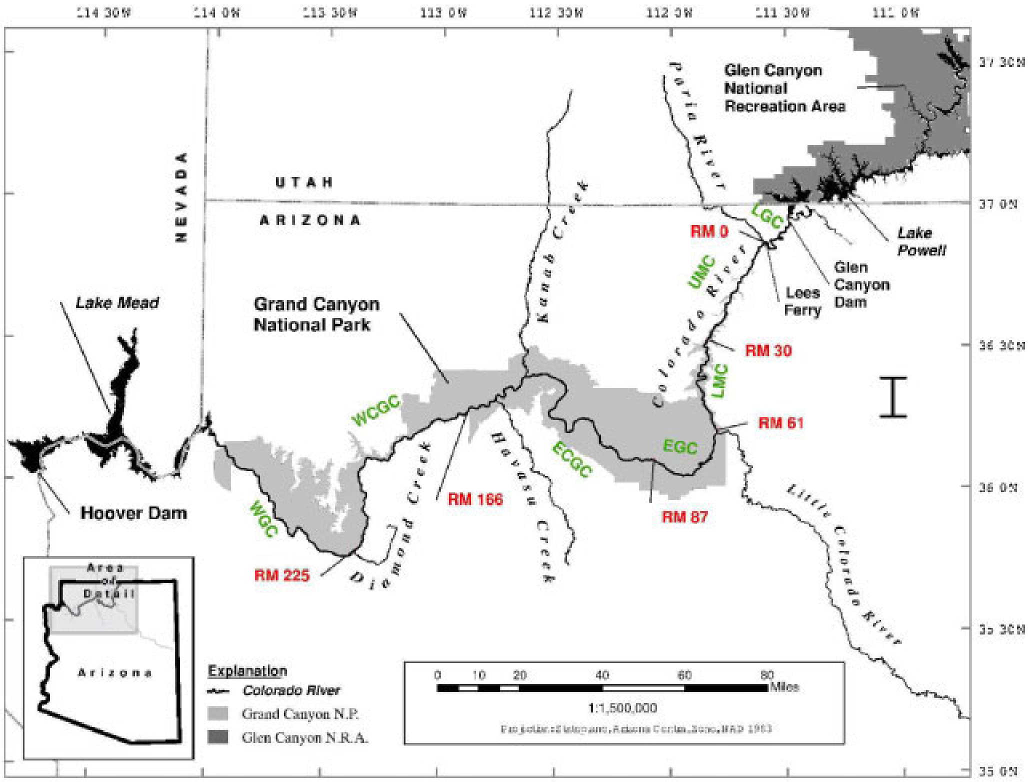

Figure 1. Map showing locations of study sites (red labels) and reaches between the study sites (green labels); RM is the abbreviation for river mile. RM 0 = Colorado River at Lees Ferry, Arizona, gaging station; RM 30 = River mile 30 sediment station; RM 61 = former Colorado River upstream from Little Colorado River near Desert View, Arizona, gaging station; RM 87 = Colorado River near Grand Canyon, Arizona, gaging station; RM 166 = former Colorado River upstream from National Canyon near Supai, Arizona, gaging station; and RM 225 = Colorado River upstream from Diamond Creek near Peach Springs, Arizona, gaging station. LGC, lower Glen Canyon; UMC, upper Marble Canyon; LMC, lower Marble Canyon; EGC, eastern Grand Canyon; ECGC, east-central Grand Canyon; WCGC, west-central Grand Canyon; and WGC, western Grand Canyon (from Topping *et al*., 2010). The use of river mile has a historical precedent and provides a reproducible method for describing locations along the Colorado River in Grand Canyon.

introduced to the river to create a sport fishery in Glen Canyon National Recreation Area (Table I). Downstream from the Lees Ferry tailwater (Figure 1), changes to river sandbars have not been as drastic because the Paria River is a source of large quantities of sand and finer sediment below the dam. However, sandbars are highly unstable and respond to relatively small changes in river flow over hourly to weekly time scales (Schmidt and Graf, 1990; Hazel *et al*., 2006). As a result, dam-induced changes have resulted in the erosion of downstream sandbars, a prominent part of the Colorado River's geomorphic landscape in Grand Canyon. Sandbars are highly valued by backcountry users as river campsites and by resource managers for the variety of riparian and aquatic habitats they create (Webb, 1996).

To mitigate sandbar erosion, a new dam-operating regime known as the Low Fluctuating Flow was implemented on an interim basis beginning in August 1991. Following completion of an environmental impact statement on the dam's operation in spring 1995, Low Fluctuating Flow rules were modified to allow higher daily peaks and the new operation was formally implemented—termed, the Modified Low Fluctuating Flow (MLFF)—by the US Department of the Interior in fall 1996. In selecting MLFF as a preferred alternative operation, it was assumed that sand delivered by tributaries downstream from the dam would accumulate on the riverbed, and periodic large releases of water from the dam would transport the accumulated sand and rebuild eroded sandbars. Water released from the dam to rebuild sandbars in Marble and Grand Canyons contains almost no fine sediment because it deposits in deltas of the low-energy setting of Lake Powell. At present, the main remaining sources of sediment to Marble and Grand Canyons are the Paria and Little Colorado Rivers (Figure 1), which cumulatively provide about 6 to 16% of the pre-dam sand supply (Wright *et al*., 2005).

As described in the *Operation of Glen Canyon Dam Final Environmental Impact Statement* (EIS) (US Department of the Interior, 1995), the 'beach/habitat-building flows,' or controlled floods, included a peak magnitude of up to $\sim 1270\,m^{-3}\,s$ and duration of up to 7 days, which is, in fact,

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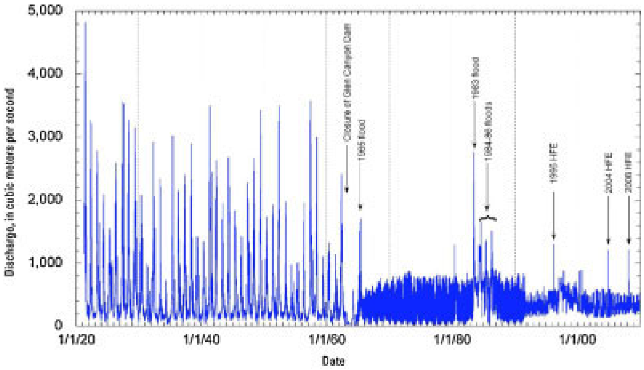

Figure 2. Instantaneous discharge (m^{-3} s) of the Colorado River at Lees Ferry (USGS station number 09380000 located at river mile 0) from May 8, 1921 to September 30, 2004 (from Wright *et al*., 2005, as modified after Topping *et al*., 2003). Before closure of Glen Canyon Dam, the annual peak flow routinely exceeded 2800 m^{-3} s. Dam operations from 1963 through 1990 were characterized by daily fluctuations from typically less than 142 m^{-3} s to near powerplant capacity, or about 878 m^{-3} s, and included the record wet period of the mid-1980s, which resulted in the use of the spillways in 1983 for emergency releases exceeding about 2549 m^{-3} s. Interim operating criteria, which constrained daily release fluctuations, began in 1991 and were followed by the MLFF operating alternative that was implemented as part of the Secretary of the Interior's Record of Decision in 1996 (US Department of the Interior, 1996) (HFE, high-flow experiment, which is another term for controlled flood).

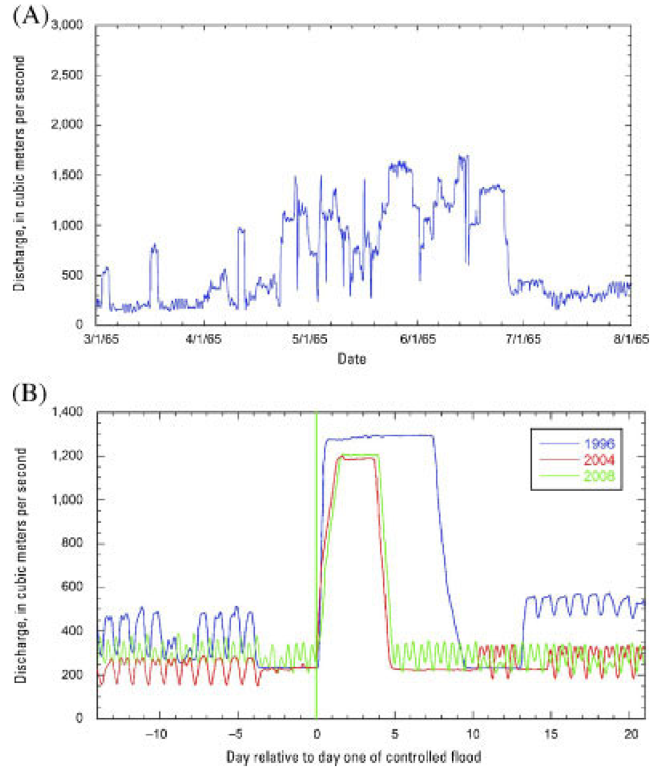

Figure 3. (A) Hydrograph at the USGS gaging station on the Colorado River at Lees Ferry, Arizona (station number 09380000) associated with Glen Canyon Dam channel-cleaning flows released during spring 1965. (B) Comparison of the flood hydrographs of the 1996, 2004 and 2008 Glen Canyon Dam controlled floods at the USGS gaging station at Lees Ferry, Arizona. These hydrographs were shifted in time such that zero time (indicated by vertical green line) is the beginning of high, steady discharge during each flood experiment. The Lees Ferry gaging station is located about 25 km downstream from Glen Canyon Dam (see Figure 1).

very similar to the magnitude and duration of channel-cleaning floods released from the dam in 1965 (compare Figure 3A,B). Based on previous studies, the 1995 EIS proposed controlled floods to rebuild and maintain eroded sandbars in Grand Canyon, although others recognized that high flows may also accelerate sandbar erosion (Laursen *et al*., 1976; Rubin *et al*., 2002). To date, it is uncertain whether there is any dam-operation strategy that can sustainably rebuild and maintain sandbars in Grand Canyon. If successful as a sandbar conservation measure, then such an operational strategy is likely to continue winnowing fine sediment from the riverbed in the Lees Ferry tailwater upstream of the Paria River.

In addition to physical alterations, dam-induced changes have resulted in the expansion of riparian vegetation, including native and non-native species, and the local extirpation of several endemic native fishes (Webb *et al*., 1999). In 1967, 4 years after Glen Canyon Dam was closed, the US Fish and Wildlife Service listed the humpback chub (*Gila cypha*) as an endangered species under the provisions of the Endangered Species Preservation Act of 1966. Long-term fisheries studies have shown that the abundance of adult populations is largely controlled by the survival rates of early life stages (e.g. Houde, 1987; Elliott, 1994). High flows released from hydroelectric dams can alter survival rates of incubating life stages of fish and affect the growth and survival of juvenile fish. However, studies of high flows relating habitat availability to fish stocks are relatively few (Sabaton *et al*., 2008). Before the March 2008 experiment, little work was done to evaluate the effects of experimental floods on fish populations in Glen, Marble and Grand Canyons (but see Valdez *et al*., 2001). Flows large enough to mobilize fine and coarse sediments during the period when eggs and alevins are incubating have the potential to scour or bury redds and therefore reduce survival rates (Holtby and Healey, 1986; Hartman and Scrivener, 1990; Magee *et al*., 1996). However, high flows can also flush fine material from the interstitial pore spaces of the stream bottom (Kondolf *et al*., 1987; Mürle *et al*., 2003), thereby potentially increasing survival for early life stages (Ortlepp and Mürle, 2003). Higher flow will increase water depth and wetted area and often provide access to off-channel habitats, potentially leading to increased survival rates for juvenile fish (Mitro *et al*., 2003; Lobon-Cervia, 2007). On the other hand, higher water velocities associated with increased flows can displace juvenile fish from preferred habitats and reduce survival (Jensen and Johnsen, 1999; Valdez *et al*., 2001; Nislow *et al*.,

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Table I. Total suspended fine-sediment (sand, silt and clay) load transported from the Lees Ferry tailwater (as measured at the Colorado River streamgage near Lees Ferry, Arizona, USGS station number 09380000) during high-flow releases from Glen Canyon Dam in 1965, March 1996, November 2004 and March 2008. Data from Topping *et al*. (2000b, 2010)

Seasonal timing of floods (planned channel-cleaning flows associated with sediment predictions)	Total suspended-sediment load (million metric tons)	Peak flow (m^{-3} s) and duration (h)	High-flow release objective(s)
Spring (March through June) 1965	~5.0 (total sand, silt and clay) in sediment year 1965 (July 1, 1964 to June 30, 1965)*	14 pulses ranging from ~500 to ~1600 m^{-3} s with varied durations (several hours to a ~week)	Engineering design and completion of hydropower plant
March 1996	0.06 ± 0.003 (sand) 0.01 ± 0.0002 (silt/clay)	~1270 m^{-3} s for 168 h	Sandbar research with multi-resource focus
November 2004	0.020 ± 0.001 (sand) 0.004 ± 0.0001 (silt/clay)	~1160 m^{-3} s for 60 h	Mainly sandbar research
March 2008	0.048 ± 0.002 (sand) 0.010 ± 0.0002 (silt/clay)	~1160 m^{-3} s for 60 h	Sandbar research with multi-resource focus

*For comparison, the average annual fine-sediment load measured at Lees Ferry during sediment years 1966–1970 was $240\,000 \pm 10\,000$ metric tons (see Figure 9a in Topping *et al*., 2000b).

2002; Einum and Nislow, 2005). Scour of benthic substrates because of high water velocities can alter the composition and abundance of the periphyton and invertebrate communities on the stream bottom and in the drift (Benenati *et al*., 2000; Shannon *et al*., 2001; Uehlinger *et al*., 2003; Rosi-Marshall *et al*., 2010), thereby affecting food availability and growth of juvenile fish (Arndt *et al*., 2002).

Despite documented scouring of the Lees Ferry tailwater resulting from the 1965 releases (Grams *et al*., 2007), floods remain the only viable means for rebuilding and maintaining eroded sandbars (Andrews, 1991; Andrews *et al*., 1999; Schmidt, 1999; Schmidt *et al*., 1999; Rubin *et al*., 2002; Topping *et al*., 2006). Colorado River resources downstream from Glen Canyon Dam have been studied with respect to the dam's operation since the 1960s. A program of controlled floods (Figure 3B) and sediment monitoring has been conducted as part of the Glen Canyon Dam Adaptive Management Program (GCDAMP) since 1996 with the scientific objective of determining whether or not an operational strategy for sandbar conservation is feasible with the limited remaining sand supply below the dam (Wright *et al*., 2005; Melis *et al*., 2007; Wright *et al*., 2008; Melis *et al*., 2010). Interaction between native and non-native fishes is currently a major area of GCDAMP research in this river and planning for future controlled floods is underway. Using experiments to reduce uncertainties and identify adaptive strategies, managers involved in the GCDAMP have identified a need to conserve sandbars while also balancing other terrestrial and aquatic resource goals, including meeting water transfer obligations, generation of hydropower, preservation of cultural resources, and preservation of native and non-native fish populations and aquatic invertebrates. The main purpose of this paper is to summarize the abiotic and biotic responses measured along the Colorado River in Glen, Marble and Grand Canyons following the controlled flood of March 2008. Management implications associated with the responses are discussed with regard to a long-term design for future flood experiments, and one possible adaptive strategy for continued flow and sandbar experimentation is discussed.

THE CONTROLLED FLOODS

During fall 2006 and 2007, Paria River floods added above average sand volumes to the Colorado River (Figure 1). By March 2008, about 1.7 million metric tons of sand had been deposited in the Marble Canyon reach of the river (Topping *et al*., 2010; UMC and LMC study reaches shown in Figure 1). In response to scientists' reports that sand enrichment of the river in Marble Canyon was well above average, the GCDAMP recommended to the US Department of the Interior that a third controlled flood be released in March 2008 (Figure 3B). The 2008 experiment was therefore conducted primarily to evaluate the sandbar-building response of a high-flow release from the dam under conditions of three to four times greater sand supply compared to the experiment in November 2004. Even so, the November 2004 flood enlarged sandbars (Melis *et al*., 2007; Topping *et al*., 2006), but only over a limited reach of about 60 km of upper Marble Canyon (UMC; Figure 1).

The hydrographs for the March 2008 and November 2004 controlled floods were virtually identical (Figure 3B). However, there were several other important differences between these two experiments. First, there was a larger mass of sand in Marble Canyon before the March 2008

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experiment, but this sand was more coarse grained than the mass of sand available before the November 2004 experiment. The sand available for the 2008 experiment was coarser because the sand from the Paria River in 2006 and 2007 had been winnowed, meaning finer sand was exported downstream by typical, but below-average dam operations (October 2006 through February 2008). In contrast, sand enrichment from the Paria River experienced winnowing for a much shorter period (mid-September to mid-November 2004) before the 2004 experiment. Median dam releases the year before the 2008 flood were slightly higher than median releases the year before the 2004 flood (Topping *et al*., 2010). The other major difference between these controlled floods was seasonal timing—late fall versus late winter. In terms of their peak durations, both the 2004 and 2008 controlled floods were much shorter than the 1996 flood (Figure 3B), but longer than some of the 1965 channel-cleaning releases (Figure 3A). Shorter duration controlled floods were suggested by scientists based on results of the 1996 experiment as implications about sand grain size and sand supply limitation in the post-dam river became more clearly understood (Rubin *et al*., 2002).

Abiotic responses—sandbars and sand mass balance

Topographic measurements made immediately after the 2008 flood indicated that sandbars were rebuilt throughout much of Marble and Grand Canyons (Hazel *et al*., 2010; Grams *et al*., 2010a, 2010b). Sandbar thickness increased in all of the sediment-transport (mass flux) study reaches (Figure 1) during the 2008 flood, except the most upstream study reach in Marble Canyon (Figure 4). Although the 1996 flood experiment was not preceded by tributary sand inputs, higher elevation sandbar responses to flooding in 1996 and 2008 were comparable at most study sites where sandbar area and volumes were measured before and after both experiments (Hazel *et al*., 2010). Sandbar measurements made 6 months following the 2008 experiment also revealed how sensitive newly deposited sandbars are to relatively small increases in daily dam releases under MLFF operations. Water supply delivery in 2008 included increased releases starting in mid-April, which were required to equalize storage between Lakes Powell and Mead (Figure 1; see hydrograph trace for April in Figure 5). Although daily peak releases associated with the increased monthly volume resulted in only about a 10% increase in daily peaks, the measured suspended-sand concentrations during the last 2 weeks of April increased by fourfold (D. J. Topping, personal communication). Sandbar data collected before and after the mid-April change in dam releases demonstrate how sensitive river sandbars are to increases in monthly volumes and resulting fluctuating flow operations (Figure 5). Glen Canyon Dam controlled floods

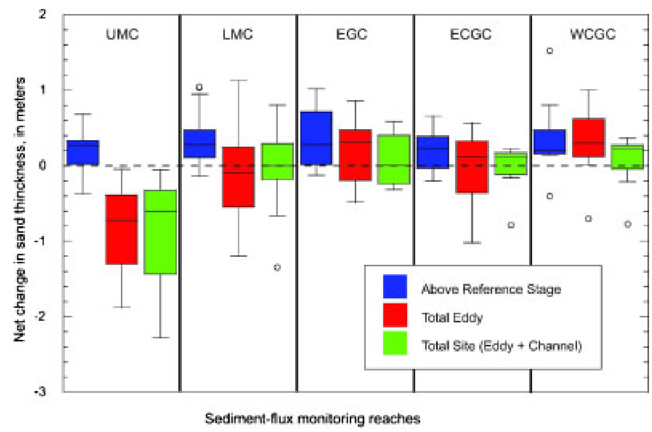

Figure 4. Downstream variations in sand thickness at study sites and suspended-sediment transport monitoring reaches in response to the March 2008 controlled flood. Upper Marble Canyon (UMC), lower Marble Canyon (LMC), eastern Grand Canyon (EGC), east-central Grand Canyon (ECGC), and west-central Grand Canyon (WCGC) reaches are shown. Boxplots show the distribution of change for above reference stage (elevation associated with 227 m^{-3} s discharge), total eddy and total site thickness within the five sediment flux-monitoring reaches. A boxplot summarizes the distribution of data by showing the interquartile range (25th to 75th percentile) as the height of the box, the median value as the centre line within the box, lines drawn to smallest and largest values within one step (equal to 1.5 times the interquartile range) beyond either end of the box, and outliers (values greater than two steps outside the box) as circles. The streamflow and suspended sediment measurement gages are located at the downstream end of each of the reaches and are 30, 61, 87, 166 and 225 river miles, respectively, downstream from Lees Ferry (river mile 0; from Hazel *et al*., 2010).

have shown that sandbars can be rebuilt over short periods using tributary sand supplies downstream from the dam. However, MLFF operations tend to erode fine-grained sand deposits. Sandbar erosion has continued despite the fact that minimum allowed annual releases from the dam have occurred in all years from 2001 to 2010, except 2008. Under average or higher annual release volumes that may be

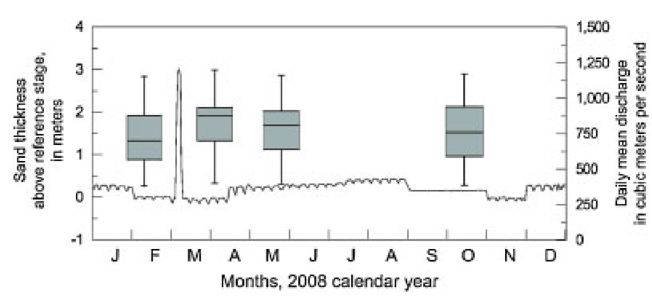

Figure 5. Boxplots showing temporal sequence of deposit thickness above the reference stage (227 m^{-3} s) compared to daily mean discharge following the March 2008 flood experiment. A boxplot summarizes the distribution of data by showing the interquartile range (25th–75th percentile) as the height of the box, the median value as the centre line within the box, lines drawn to smallest and largest values within one step (equal to 1.5 times the interquartile range) beyond either end of the box (from Hazel *et al*., 2010).

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required for future water transfers, new sandbar erosion will likely occur at even higher rates, perhaps similar to those documented in the era before dam operations changed in summer 1991 (Schmidt and Graf, 1990). Despite ongoing sandbar erosion, monitoring data indicate that 74% of sandbars studied in Grand Canyon were slightly larger (volume) in October 2008 than prior to the 1996-controlled flood, although measured sandbars in Marble Canyon remained about the same size (Schmidt and Grams, 2011).

Erosion rates for new sandbars following return to MLFF operations after each of the three controlled floods since 1995 varied greatly. Monitoring data suggest that sandbars resulting from these floods last longest (Figure 6) under conditions of lowest mean daily discharge and highest post-flood tributary sand supply (Grams *et al*., 2010a). However, it is not clear which of the two factors plays the greater role in sandbar stability. Tributary sand supply is highly variable, and only a program of sand augmentation (Randle *et al*., 2007) might guarantee consistently higher sand supplies that may be important for maintaining bars following repeated floods from the dam. Upper Colorado River Basin hydrology is also highly variable and higher annual volume dam releases to meet downstream water supply transfers are required during wetter periods. Without the ability to augment the river's sand supply from upstream sources in Lake Powell or constrain annual release volumes, further stabilizing daily and seasonal patterns of flow between sandbar building releases is likely the only means available to managers for slowing erosion rates after new sandbars are built (Wright *et al*., 2008).

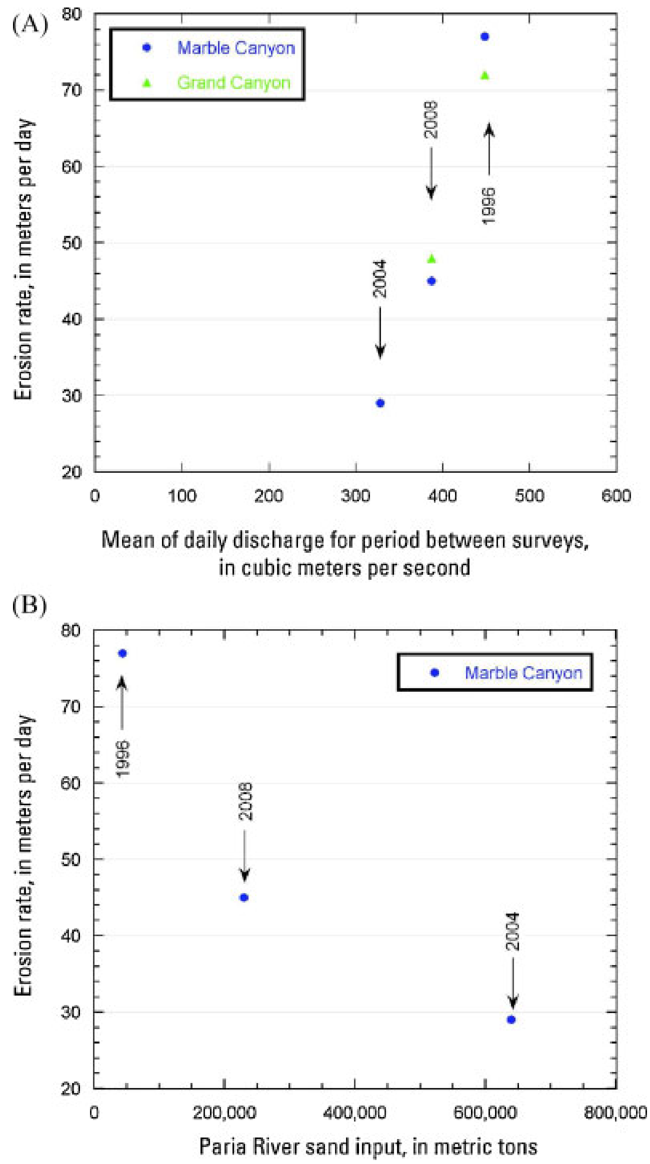

Figure 6. Comparison of sandbar erosion rates under different dam operations and tributary sand delivery to the Colorado River following each of the three controlled-flood sandbar-building responses. (A) Rate of sandbar erosion as a function of the mean of mean daily discharge for periods between post-flood surveys and 6-month post-flood surveys for sites in Marble Canyon, eastern Grand Canyon, and combined central and western Grand Canyon. Each year is associated with a single mean of daily discharge, as indicated. (B) Rate of sandbar erosion as a function of the total magnitude of Paria River sand inputs that occurred in the period between post-flood surveys (from Grams *et al*., 2010a). This figure is available in colour online at wileyonlinelibrary.com/journal/rra.

Biotic responses—rainbow trout and food availability in the Lees Ferry tailwater

The effect of the March 2008 controlled flood on early life stages of rainbow trout in the Lees Ferry tailwater was evaluated by comparing growth and survival in years before and after the release. Multiple lines of evidence indicated that the 2008 flood resulted in a large increase in early survival rates, apparently owing to an improvement in habitat conditions and food availability (Rosi-Marshall *et al*., 2010; Kennedy and Ralston, 2011; Cross *et al*., in press; Korman *et al*., in press). Age-0 abundance in July 2008 was more than fourfold higher than expected given the number of viable eggs that produced these fish (Figure 7). A hatch-date analysis indicated that early survival rates (fertilization to about 2 months from emergence) were much higher for cohorts that emerged 2 months or more after the flood (Figure 8). Average growth rates of age-0 trout in the summer of 2008 were virtually the same as in 2006 (Figure 9), even though abundance was about eight times greater in 2008. As growth of juvenile salmonids often declines at higher density (Jenkins *et al*., 1999; Nislow, 2001; Imre *et al*., 2005; Ward *et al*., 2007), this likely indicates that the quality of the rearing environment for age-0 trout improved after the March 2008 controlled flood, overriding the effect of high abundance on growth.

Suspended fine-sediment concentrations measured during the 2008 flood indicate that the amount of sand, silt and clay

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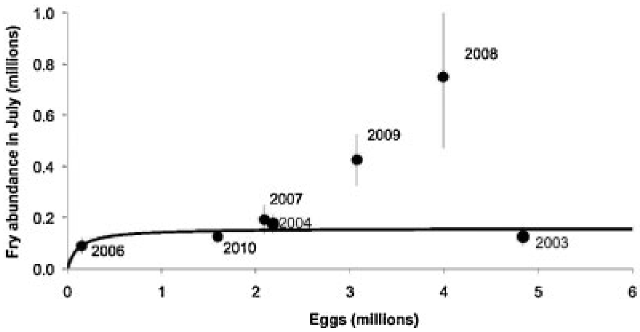

Figure 7. Relationships between the number of viable eggs in the Lees Ferry tailwater (0–25 km upstream of the Paria River) and the resulting population size of age-0 trout on July 15th, 2003–2010 (no data collected in 2005). The thick black line shows the best-fit stock-recruit model using data from 2003 to 2007 only. The light gray vertical lines show the 95% confidence limits for the age-0 abundance estimates (from Korman *et al*., in press).

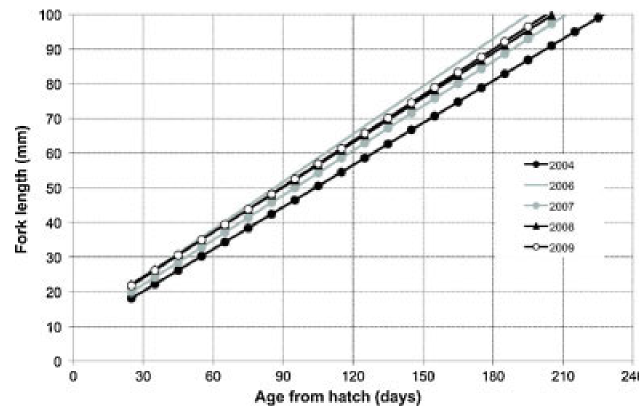

Figure 9. Comparison of annual length-at-age relationships for age-0 rainbow trout in the Lees Ferry tailwater (0–25 km upstream of the Paria River). Relationships were based on daily age estimates determined from analysis of otolith microstructure ($n = 1044$ summed across 6 years). Note that year-specific relationships were relatively precise, with age predicting 82–93% of the variation in length among individuals (from Korman *et al*., in press).

evacuated from the Lees Ferry tailwater was 2.4 times higher than the fine-sediment mass exported from the reach during the November 2004 flood (Table I; Topping *et al*., 2010). Hence, it is likely that going into the 2008 flood, gravels were clogged with fine sediment and/or decaying organic matter, and the March controlled flood increased interstitial spaces in the gravel substrate of the bed. Suspended-sediment transport measurements indicate that the 2008

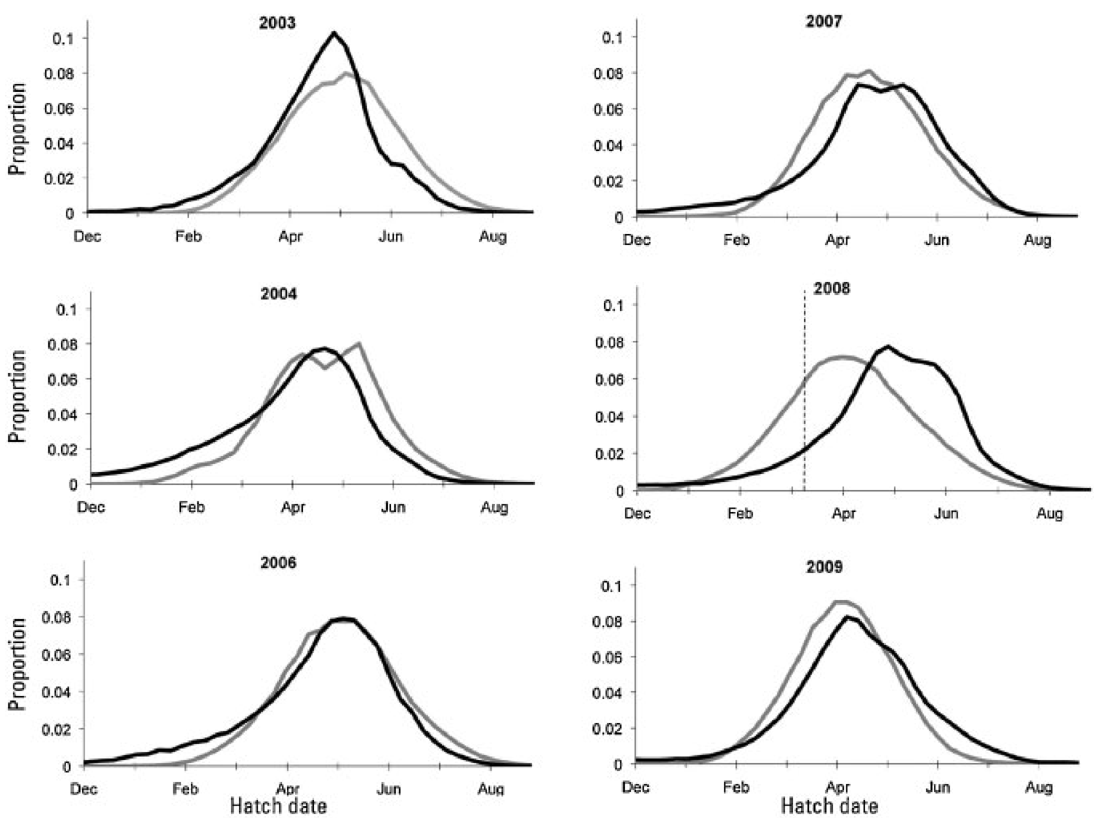

Figure 8. Comparison of back calculated (black line) and predicted (gray line) hatch date distributions. Predicted distributions were determined based on spawn timing and temperature-dependent incubation time. Survival of weekly cohorts is poorer than expected when the predicted proportion exceeds the back calculated proportion, and better than expected when the opposite occurs. The vertical dashed line for the 2008 plot identifies the date of the March 2008 controlled flood (from Korman *et al*., in press).

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flood (60-h peak) exported 83% as much sand, silt and clay as the March 1996 flood (168-h peak) experiment. Although the fine sediment supply to Glen Canyon is much lower than to downstream reaches, the controlled flood data suggest that sediment can accumulate in the tailwater through time, yet is evacuated from the bed during floods. Studies by Wilcock (1998) suggest that the presence of sand and gravel can greatly influence bed mobility in gravel-bed channels like the one found in the Lees Ferry tailwater. Intermittent tributary sand inputs to the tailwater downstream from Glen Canyon Dam might therefore influence gravel mobility during future floods. Hence, continued channel cleaning may occur in ways that enhance spawning habitat and rainbow trout production following floods intended to rebuild sandbars.

The 2008 controlled flood reduced annual invertebrate production in the Lees Ferry tailwater by more than 50% (Table II). This was driven primarily by significant reductions in the production of New Zealand mudsnails (*Potamopyrgus antipodarum*) and freshwater shrimp (*Gammarus lacustris*). However, production of two less common taxa—chironomid midges (Family Chironomidae) and black flies (Family Simuliidae)—actually increased the year after the 2008 flood. Concentrations of invertebrate prey available in drift increased from an average of 0.093 mg m^{-3} ash-free dry mass (AFDM) (with a 95% confidence interval of 0.073–0.117) before the flood, to an average of 0.163 (0.127–0.208) after the flood (Rosi-Marshall *et al*., 2010; Cross *et al*., in press). The increase in invertebrate drift that occurred after the flood experiment was driven by large increases in the concentrations of midges and black flies (400–800% increase), which are prone to drifting and frequently consumed by salmonids (Radar, 1997). Thus, although the 2008 flood reduced total invertebrate production, it actually increased the amount of invertebrate prey available to rainbow trout by shifting the invertebrate assemblage toward species that are prone to drifting (Cross *et al*., in press). It is likely that these changes in the prey base led to increases in the growth and survival of young trout that emerged 2 or more months after the flood (Korman and Melis, 2011; Korman *et al*., in press). Both age-0 growth and abundance in 2009 were higher than expected given age-0 abundance and the number of viable eggs deposited in that year, which suggests the effect of the 2008 flood on early life stages may have persisted into 2009, but 2010 data reveal levels similar to 2006–2007. Monitoring data for rainbow trout in Marble Canyon between 2000 and 2009 indicate that catch per unit effort for trout downstream from the Lees Ferry tailwater increased in 2009 to levels not observed since 2000, probably as a result of the strong 2008 cohort produced after the flood (Makinster *et al*., 2010).

IMPLICATIONS OF 2008 FLOOD RESPONSE FOR RIVER MANAGEMENT

Initial studies of sand transport and sandbar erosion predicted that sandbar loss in Grand Canyon was inevitable following construction of Glen Canyon Dam and that the loss might occur over a long (i.e. up to 1000 years) and uncertain timeframe (Laursen *et al*., 1976). Despite three decades of additional data collection and experimental flow

Table II. Invertebrate secondary production in milligrams AFDM m^{-2} year^{-1} (95% confidence intervals) in the Lees Ferry tailwater of the Colorado River, Arizona, USA, between July 2006 and June 2009. Lower case letters [a,b,c] indicate significant differences in production for given taxa among years, based on non-overlapping confidence intervals. Data from Dr. Wyatt Cross, Montana State University, and modified from Rosi-Marshall *et al*. (2010)

Taxon	Year 1 (July 06–June 07)	Year 2 (July 07–June 08)	Year 3 (July 08–June 09)
Potamopyrgus antipodarum	13 300 (10 200–16 700)^{a}	10 700 (6800–17 000)^{a}	2000 (1640–2390)^{b}
Gammarus lacustris	7010 (5400–9000)^{a}	8 690 (6540–11 000)^{a}	2650 (2100–3350)^{b}
Tubificidae (a)	4290 (3540–5070)^{a}	2860 (2320–3480)^{b}	3930 (3310–4670)^{ab}
Turbellaria	754 (577–983)^{a}	382 (287–489)^{b}	577 (428–748)^{ab}
Physidae	1080 (676–1630)^{a}	494 (373–627)^{b}	500 (388–626)^{b}
Lumbricidae	706 (526–905)^{a}	5470 (2540–9400)^{b}	634 (428–859)^{a}
Chironomidae	559 (433–690)^{a}	657 (548–757)^{a}	937 (808–1070)^{b}
Ostracoda	274 (183–377)^{a}	70.4 (53.0–90.2)^{b}	31.0 (26.0–35.9)^{c}
Nematoda	116 (95–142)^{a}	127 (92–167)^{a}	215 (184–249)^{b}
Sphaeridae	116 (41.4–219)^{a}	28.7 (2.20–58.2)^{a}	62.0 (43.0–84.8)^{a}
Simuliidae	49.3 (21.1–83.5)^{a}	348 (141–604)^{b}	1180 (672–1820)^{c}
Cladocera	37.2 (25.6–49.8)	45.9 (17.0–85.4)	53.0 (35.6–72.8)
Copepoda	35.7 (26.0–46.5)	29.0 (19.3–40.1)	37.0 (28.6–45.6)
Tubificidae (b)	57.0 (27.7–109)	27.2 (12.5–46.0)	86.0 (53.0–124)
Ceratopogonidae	0.000779 (0.0000267–0.00219)	0.000130 (0–0.000328)	0
Acari	0.000917 (0.000273–0.00189)	0.0000448 (0.0000962–0.00000469)	0

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research, this conclusion has not yet been refuted by researchers. Studies since 1990 have shown that without periodic floods that occur under sand-enriched conditions, eroded sandbars cannot be rebuilt at higher elevations along shorelines. Three controlled floods released from the dam have temporarily rebuilt sandbars since 1996, but it is clear that sandbar building through flooding cannot be sustained unless floods are timed to follow tributary sand inputs. Further, even when properly timed, sandbars are eroded quickly under releases associated with currently approved MLFF dam operations (Hazel *et al.*, 2010; Grams *et al.*, 2010a, 2010b).

Despite the learning that has occurred from the three controlled floods, the long-term fate of Grand Canyon sandbars is still highly uncertain (Wright *et al.*, 2008). Researchers have identified the need for a long-term experimental approach of releasing floods of limited duration and magnitude to match tributary sand deliveries (Wright and Kennedy, 2011). It is suggested that these controlled floods occur over a period of a decade or longer, whenever sand supply is enriched below the dam by tributaries. A strategy of controlled floods following downstream tributary sand inputs may be able to incrementally rebuild and maintain sandbars in a cumulative and sustainable manner (Topping *et al.*, 2006). However, even with repeated floods following each tributary sand input, continued sandbar erosion may not be mitigated in Grand Canyon National Park without other measures. Measures such as sand augmentation from upstream sources in Lake Powell (Randle *et al.*, 2007), additional dam operating constraints to achieve more stable flows between floods, or both, might still need to be considered if desired sandbar conditions cannot be achieved with the existing sand supply under current MLFF operations.

One adaptive strategy for reducing uncertainty about whether there is sufficient sand supply downstream from the dam to rebuild and maintain sandbars might follow an experimental path toward increased flow stability (Figure 10). In such a sediment experiment, the key element for successful sandbar conservation would be release of floods whenever enough tributary sand enters the Colorado River. These floods might be combined with intervening daily flows ranging from unconstrained hydropeaking releases that meet energy demand to steady year-round flows. Sandbar monitoring would continue between controlled floods over perhaps a decade or longer with annual assessment by managers to determine if sandbar objectives are being achieved. Results so far from the three controlled floods suggest that one possible next step in Grand Canyon sandbar experimentation might be to increase the frequency of sand-enriched floods (to match sand input events) and monitor sandbar fate under currently approved MLFF daily operations. If sandbars continue to erode between floods such that the net sand storage is decreased (continued net sand deficit), then the next phase of evaluation would logically be to increase flow stability between sand-enriched

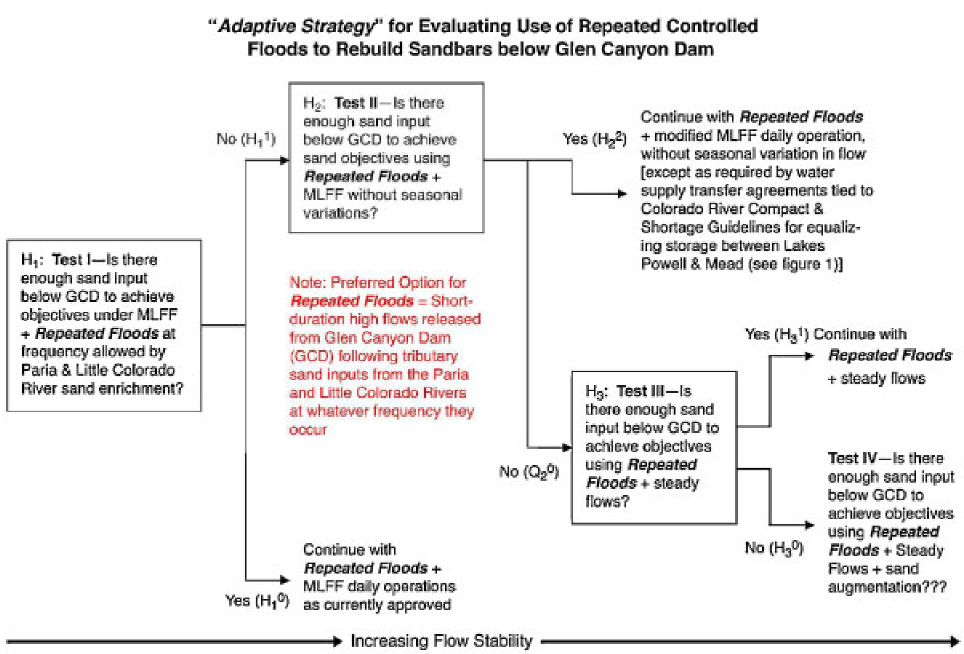

Figure 10. Decision tree showing one adaptive strategy for monitoring controlled floods released from Glen Canyon Dam to determine whether there is sufficient downstream tributary sand supply to rebuild and maintain eroded sandbars within Grand Canyon National Park. Additional information about estimates for achieving sandbar objectives under steady flows is found in Wright *et al.* (2008).

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floods (Figure 10). Under this conceptual design, the experimental floods in Figure 10 would continue to be released until sediment objectives are either met or managers and scientists reach a determination that the existing sand supply from tributaries below the dam is not sufficient to rebuild and maintain sandbars. Because such a determination can only be made after considering the range of upper Colorado River Basin hydrology and required downstream water transfers, a long-term experimental approach is required.

Although continued controlled floods are suggested as the only means of reducing uncertainty about the long-term fate of Grand Canyon sandbars, such experiments also present a risk because more frequent floods might also accelerate the rate of sand loss downstream from the dam (Rubin *et al*., 2002; Wright *et al*., 2008). Additionally, flood-driven increases in the abundance of non-native rainbow trout might be in conflict with goals for native fish populations that occur downstream of the tailwater in Grand Canyon, including Federally-listed humpback chub. The sediment experiment shown in Figure 10 might pursue more stable intervening flows between floods to decrease sandbar erosion, but will also possibly favour non-native fish survival following flood-enhanced trout production (recruitment). Large numbers of rainbow trout appear to emigrate from the Lees Ferry tailwater to Marble Canyon (Makinster *et al*., 2010) and pose a threat to native fish persistence because of increased competition for food and habitat and predation (Coggins, 2008; Coggins and Yard, 2010; Yard *et al*., in press). While planning for future experimental floods continues, the Bureau of Reclamation and other managers are also evaluating options for controlling non-native fish abundance below the dam. One option for non-native fish control includes physical removal of trout and other non-natives in lower Marble Canyon where humpback chub are found. Other experimental options that might also be considered include physical removal of non-native fish from upper Marble Canyon, strategically using dam releases to limit juvenile rainbow trout survival following controlled floods, sediment augmentation to Marble Canyon to increase turbidity, or combinations of the above.

Inferences about the effects of future spring floods on early survival and growth of early life stages of fish are limited by the fact that only one spring experiment has been carefully evaluated to date. Ideally, monitoring of early life stages of both native and non-native fish will continue to determine if the responses from future spring flood experiments are similar to those observed in 2008. The conclusion that spring floods increase survival of early life stages of rainbow trout is consistent with the historical recruitment trend estimated using a statistical catch-at-age model applied to adult catch data (C. J. Walters, personal communication). This analysis showed that recruitment of juvenile trout in 1997, 1 year after the first controlled flood in March 1996, was 2.8 times greater than other estimates of recruitment during the 1990s (Makinster *et al*., 2010). Of the three floods conducted to date, the 1996 flood removed the largest mass of fine sediment from the bed of the tailwater (Table I). Hence, the longer-duration 1996 flood was more effective at 'channel cleaning' than was the 2008 experiment, but considering its shorter duration, the 2008 flood was the most efficient at cleaning the channel bed of the Lees Ferry tailwater. The 2008 observation is also consistent with increased catch rates of age-0 trout downstream from Glen Canyon Dam after the 1996 controlled flood (Valdez *et al*., 2001) and positive responses of salmonid populations to tailwater floods released from dams in other river systems (e.g. Ortlepp and Mürle, 2003). To date, no direct effects on native fish of the Colorado River have been measured in response to the 1996, 2004 or 2008 controlled floods released from Glen Canyon Dam (Kennedy and Ralston, 2011).

The aquatic food web responses measured following the 2008 flood suggest that the effects of spring flooding on invertebrates may persist up to 15 months in the Lees Ferry tailwater (Rosi-Marshall *et al*., 2010; Cross *et al*., in press). If controlling the abundance of exotic New Zealand mudsnail (*P. antipodarum*) in the tailwater is a goal of river managers (see Cross *et al*., 2010), then the 2008 flood results indicate that similar flooding perhaps every 2–3 years might also be effective at limiting mudsnail abundance over time. More frequent floods under tributary sand enrichment, suggested by sediment researchers as a means of answering sandbar conservation questions (Topping *et al*., 2006; US Geological Survey, 2008; Wright *et al*., 2008), may also cause a shift in the state of the benthic invertebrate assemblage of the Lees Ferry tailwater. One possibility is for a shift toward lower overall invertebrate biomass, but higher quality food resources that can benefit the rainbow trout population below the dam. Floods are known to increase the abundance of food consumed by rainbow trout in numerous streams and rivers (Radar, 1997, and references therein).

A long-term programme of controlled floods at Glen Canyon Dam is now being proposed by river managers. In support of controlled flood planning, researchers have also outlined a triggering strategy for future floods that considers historical timing and frequency of downstream tributary sand deliveries below the dam (Wright and Kennedy, 2011). Such a long-term programme has the potential to resolve uncertainties about whether sandbars can be rebuilt and maintained with the limited sand supply that exists downstream from the dam. Rainbow trout and food web responses measured in response to the 2008 flood suggest that biotic responses to spring flooding are perhaps more persistent than the sandbars created during the controlled floods. Although one fall flood occurred in November 2004,

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little is known about the biotic responses of that experiment. Implications of the rapid erosion of new sandbars are that other experimental measures may be required to achieve sediment objectives, including perhaps testing of more stable flow release patterns or sand augmentation. Owing to the fact that sandbar, non-native fish and aquatic food responses were linked to at least one spring-timed flood release from the dam, similar future experiments must be carefully coordinated between sediment researchers and biologists to reduce uncertainty about trout responses and downstream interaction between native and non-native fish in Grand Canyon (Korman and Melis, 2011). Controlled floods in the fall, when most Paria River sand inputs usually occur, will likely provide the greatest benefit to sandbars and may or may not increase trout abundance below the dam. Spring floods following less frequent winter sand inputs, in contrast, could also be important in future sandbar experiments, but might also sustain trout increases that pose a threat to humpback chub in Grand Canyon National Park.

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